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A monolithic LWIR/NIR multispectral QWIP for night vision and see spot

N. Cohen ^{*}, A. Zussman, G. Sarusi

Elop, Electrooptic Industries Ltd., Rehovot 76111, Israel

Abstract

A two stack two color quantum well infrared photodetector (QWIP) for simultaneously detection of LWIR and near infrared (NIR) radiation is demonstrated. The LWIR sensor is based on a regular GaAs/AlGaAs QWIP, while the NIR sensor is based on a strained InGaAs/GaAs quantum wells structure. Optical and electrical measurements of the NIR detector and the inclusive device are presented and discussed. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Among end-users of thermal imaging systems there is a strong demand for multispectral systems. A suitable candidate for such systems is the quantum well infrared photodetector (QWIP). The QWIP technology enables us to design and fabricate arrays sensitive simultaneously to the two spectral bands 3–5 and 8–12 μm [1,2], or in several narrow bands within one of the spectral regions [3,4]. Another important military application of multispectral system is a “see spot”, i.e. a system that can sense a near infrared (NIR) laser spot together with the LWIR thermal image.

In this work we have designed and fabricated a monolithic dual band QWIP sensitive to both the LWIR (peaked to 8.8 μm) and to the NIR spectral regions. A GaAs based QWIP was chosen due to its more advanced and reliable technology compared with other technologies. To sense NIR ra-

diation in a GaAs based structure, InGaAs alloys must be used, as will be described below.

2. Experimental

Two samples, which differ essentially in the indium concentration of the InGaAs layers, were grown by QED Inc. on semi-insulating GaAs substrates by molecular beam epitaxy. As can be seen in Fig. 1, the structure contains two stacks.

The first stack is a regular intersubband transition QWIP detector, sensitive to the LWIR spectral region. The second stack is based on interband transition InGaAs/GaAs quantum wells, and sensitive to the NIR spectral region. Two different structures were grown one with 35% indium mole fraction, and the other with 30% indium mole fraction. Three contact layers were defined top, bottom and middle.

To operate the device properly under a regular two-pole bias, the structure was designed so the bias will be distributed equally between the two

^{*} Corresponding author.

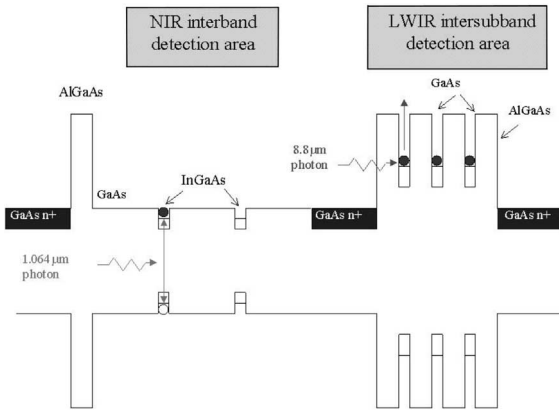


Fig. 1. Schematics of the structure.

sensing regions. To facilitate this requirement an AlGaAs barrier was added. This enables one, by changing the barrier height and width, to take care of the relative impedance of the two stacks.

Since GaAs and AlGaAs are transparent to the NIR, InGaAs was used as an absorption layer for this band. The transition wavelength of the InGaAs layers depends on the indium mole fraction and the layer thickness. As known there is an inherently mismatch between the GaAs and the InGaAs lattice constant. Therefore, the layer thickness of the InGaAs grown on GaAs should not exceed a critical thickness to avoid a strain relaxation which gives rise to dislocations and thus degrade the device performances. It must be emphasized that there is a large disagreement in literature regarding the dependence of the critical thickness on the indium mole fraction [5–8]. In order to fit the InGaAs composition and thickness to the NIR wavelength, we relied on the analysis given in Refs. [5,8,9]. In order to ensure that all the strain will be confined in the InGaAs layer, the thickness of the GaAs barriers were chosen to be sufficiently large (3000 Å).

The optical properties of the structure were examined using the photoluminescence (PL) technique. Using standard photolithography techniques $200 \times 200 \mu\text{m}^2$ mesas were fabricated. The mesas contained only the NIR detector region (top to middle contact). Dark current and spectral response measurements were taken in several temperatures. Second $200 \times 200 \mu\text{m}^2$ mesas were

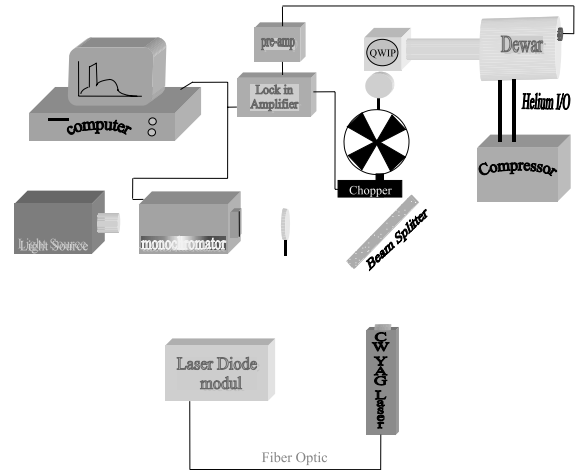


Fig. 2. Experimental setup for laser sensing over the thermal response.

fabricated, containing both stacks (top to bottom contact). Reflecting gratings were defined on top of the structure, to enable the ISBT transitions at the LWIR stack. LWIR and simultaneously LWIR/NIR response measurement were taken. The setup for the simultaneously LWIR/NIR response measurement is shown in Fig. 2.

The system contained a standard setup for 8–12 μm spectral response measurement, i.e. light source, monochromator, optics, chopper, lock-in amplifier and a computer control unit.

3. Results and discussion

3.1. Optical measurements

The PL spectrum of the 35% indium based structure is shown in Fig. 3. As can be seen the peak wavelength fits the designed 1064 nm. The observed linewidth, however, is about 23 meV, which is few times wider than that of a typical lattice-matched PL line. This may indicate a partially relaxed structure.

A much narrower PL spectrum was obtained in the 30% indium based structure as shown in Fig. 4.

This result may indicate that this structure is fully strained.

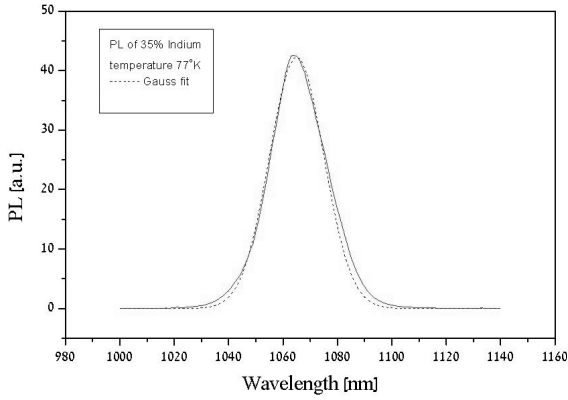


Fig. 3. PL spectrum of the 35% indium structure at 77 K.

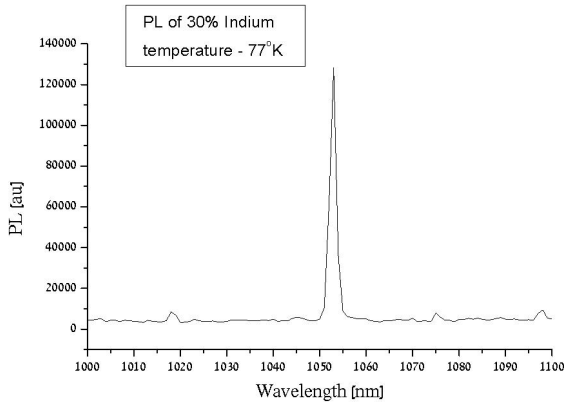


Fig. 4. PL measurement of the 30% indium structure at 77 K.

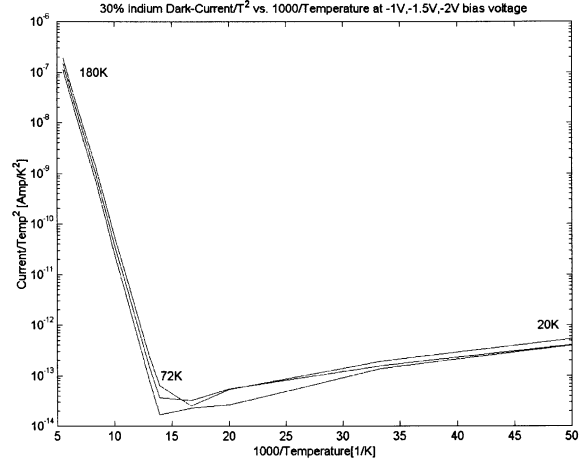
3.2. Dark current measurements

The main purpose of the top AlGaAs barrier is to limit the dark current. Charge carriers can penetrate through the barrier by tunneling and thermionic emission. The current due to thermionic emission can be written as:

$$I_{te} = AT^2 \exp\left(-\frac{\phi_B}{kT}\right) \quad (1)$$

where ϕ_B is the barrier height. The dark current divided by T^2 vs $1/T$ is shown in Fig. 5.

It is evident from this figure that the temperature dependence of the current at low and high temperatures are different, indicating different current mechanisms in the two regions.

Fig. 5. Dark current of the 35% indium based structure divided by T^2 vs $1/T$.

The results can be explained by a current mechanism dominant by thermionic assisted tunneling at low temperatures, and a thermionic emission at the higher ones. In the high temperatures range activation energy of 160 meV was derived. The AlGaAs barrier is 224 meV high and the Fermi level at the contact layer is 34 meV. This gives an effective barrier of 190 meV. However, since a large fraction of the applied voltage falls on barrier, one expects a large image charge barrier lowering. Thus, for a barrier voltage drop of 1 V a barrier lowering of about 40 meV is obtained, giving a reasonable agreement between the observed and calculated effective barriers.

3.3. Spectral response measurements

Spectral response was measured at several temperatures. Typical results at 72 K – 3 V bias are shown in Fig. 6.

The experimental data was fitted to transition spectra composed of three lines, using Gaussians lineshapes. The best fit calculation yield the wavelength 898, 947 and 1054 nm, in good agreement with the calculated values of InGaAs HH2 E2 (884 nm), InGaAs LH1 E1 (913 nm) and InGaAs HH1 E1 (1064 nm) respectively.

The measured response in the 30% indium based structure at 1064 nm, 77 K and –3 V bias was 0.04 A/W.

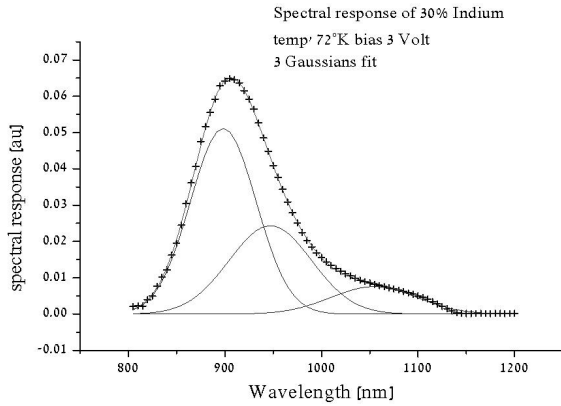


Fig. 6. Spectral response of NIR stack.

The responsivity (R) can be written in the standard used for photoconducting detectors:

$$R = \frac{q}{h\nu} \eta g \quad (2)$$

where q is the electron charge, h is Planck constant and ν is the light frequency. The quantum efficiency η can be written as:

$$\eta = \eta_0 P_e \quad (3)$$

where η_0 is the efficiency of converting the NIR photons into charge carriers at the lower energy level of the quantum well, and P_e is the probability of charge carrier in this level to escape to the continuum. For small absorption:

$$\eta_0 \cong \alpha L_w \quad (4)$$

where α is the absorption coefficient for interband transitions, and L_w is the well width. For a thermal process the escape probability is given by:

$$P_e = \exp\left(-\frac{V - E_1}{kT}\right) \quad (5)$$

where V is the barrier height, E_1 is the lowest energy level at the well, k is Boltzmann constant and T is the temperature.

The gain g is given by:

$$g = \tau_L / \tau_t \quad (6)$$

where τ_L is the lifetime of excited charge carrier in the lowest energy level of the well, and τ_t is the

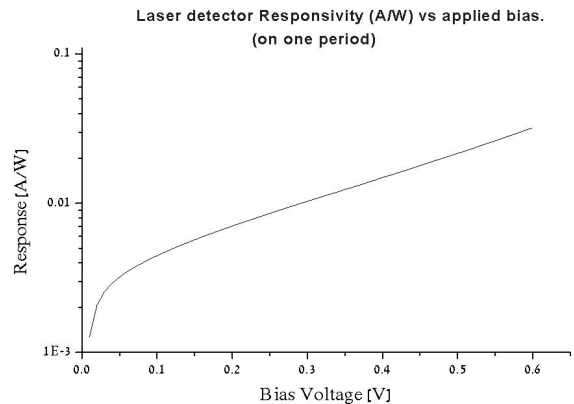
transition time of charge carrier over one period of the structure. Typical lifetime of strained InGaAs layers is 1 μ s [10]. This value is much larger than the 1 ps typical lifetime of intersubband transition. Thus InGaAs NIR detector gain is a few orders of magnitude higher than that of the LWIR QWIP.

We have calculated the current responsivity vs bias for this structure using a model which takes into account the thermionic emission and thermally assisted tunneling, including image charge barrier lowering [11]. For the 30% indium based structure with a band offset ratio of $V_c:V_v = 60:40$, the conduction band barrier is 224 meV. For a well width of 60 Å the lowest energy level (E_1) is 65 meV. The calculation yields a responsivity which is about six orders of magnitude smaller than the observed one. This large discrepancy between the observed and calculated values can be attributed to the band offset of 60:40 used in the calculation. In the literature a rather wide range of band offset values is reported for InGaAs, extending from 90:10 to 35:65 [12].

The calculated current responsivity vs bias for a band offset ratio of 40:60 is shown in Fig. 7.

In this calculation the potential drop on the AlGaAs barrier was neglected, and the bias was assumed to be uniformly distributed over the five wells of the NIR stack.

As can be seen the calculated responsivity of the 30% indium based structure at -3 V bias is 0.03 A/W in good agreement with the measured one.

Fig. 7. Calculated responsivity vs bias (one period) of NIR stack. $T = 77$ K band offset 40:60.

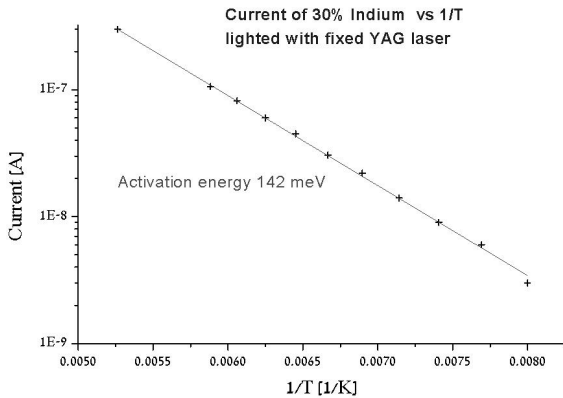


Fig. 8. Response current of 35% indium based structure under fixed YAG laser illumination vs $1/T$ in temperature range of 125–200 K.

In order to check out the validity of our assumption regarding the band offset ratio, a photocurrent experiment was carried out on the 35% indium based structure using as a constant radiation source a CW YAG laser at 1064 nm. The photocurrent under the laser radiation was measured as a function of temperatures in the range of 125–200 K as shown in Fig. 8.

The photocurrent varies exponentially with $1/T$, with an activation energy of 142 meV. In this temperature range the shift in the position of the peak at the PL is much smaller than the linewidth, i.e. the absorption of the laser radiation is almost constant in this temperature range. The value of the activation energy does not match the 60:40 offset ratio, which corresponds to a calculated effective activation energy of 185 meV.

It must be emphasized that the change in calculated energy transitions of the 40:60 offset ratio compared to the 60:40 case, is negligible.

The spectral response of the LWIR region of the device can be seen in Fig. 9.

A peak responsivity of 0.15 A/W was measured at 77 K for a bias of -3 V applied on the entire device containing both stacks (top to bottom contacts).

This response is much lower than the responsivity of 0.45 A/W, which we obtained for a LWIR QWIP without a NIR stack [13]. Two factors can contribute to this difference. Firstly, in this struc-

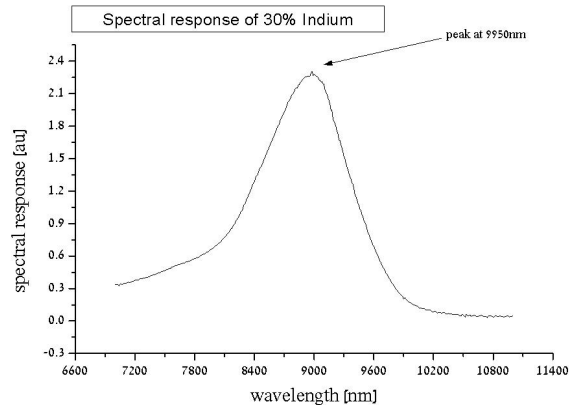


Fig. 9. Spectral response of the 30% indium alloy structure.

ture due to the larger impedance of the NIR stack, smaller fraction of the bias falls on the LWIR stack. Secondly, since the NIR stack is located below the reflecting mirror, the optical coupling to the LWIR stack is reduced.

The operation of the device as a dual band detector was demonstrated using the setup shown in Fig. 2.

During the wavelength scanning a 10 mW radiation of a CW YAG (1064 nm) laser was applied for a limited time. The results are shown in Fig. 10.

The response of the detector to the NIR laser radiation can clearly be seen over the thermal response. This result indicates that the device is

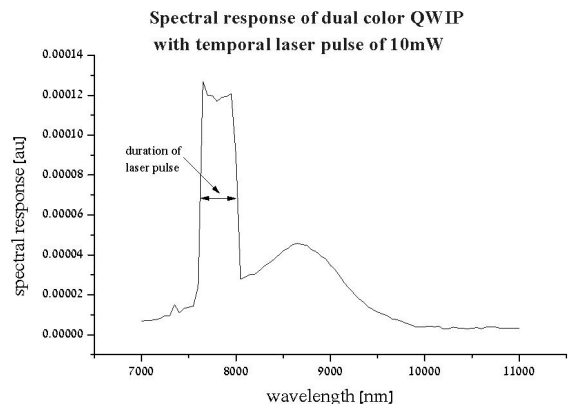


Fig. 10. Spectral response of the 30% indium based structure interrupted by a 1064 nm laser pulse (two pole -3 V bias, 72 K).

capable of sensing simultaneously the two spectral bands.

4. Conclusions

A simultaneously dual band QWIP for the LWIR and NIR spectral band was presented. The electrical and optical measured results indicates that it is possible to realize with this device a thermal imaging system that can sense a laser spot. An effort must be done to optimize the device for the end users needed applications.

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References

- [1] B.F. Levine J. Appl. Phys. 74 (8) (1993).
- [2] K.L. Tsai, K.H. Chang, C.P. Lee, K.F. Huang, J.S. Tsang, H.R. Chen, Appl. Phys. Lett. 62 (26) (1993).
- [3] H. Schneider, F. Fuchs, B. Dischler, J.D. Raslton, P. Koidl, Appl. Phys. Lett. 58 (20) (1991).
- [4] M.Z. Tidrow, X. Jiang, S.S. Li, K. Bacher, Appl. Phys. Lett. 74 (9) (1999).
- [5] D.J. Arnet, K. Deneffe, C. Van Hoof, J. De Boeck, G. Borghs, J. Appl. Phys. 66 (4) (1989).
- [6] B. Elman, E.S. Koteles, P. Melman, K. Ostreicher, C. Sung, J. Appl. Phys. 70 (5) (1991).
- [7] G. Ji, D. Huang, U.K. Reddy, T.S. Henderson, R. Houdre, H. Morkoc, J. Appl. Phys. 62 (8) (1987).
- [8] E.A. Fitzgerald, Properties of lattice matched, strained indium gallium arsenide, INSPEC publication, 1993, pp. 6–15.
- [9] A. Shappir, M.Sc. Thesis, Tel-Aviv University, 1999.
- [10] S. Adachi, Properties of lattice matched, strained indium gallium arsenide, INSPEC publication, 1993, pp. 84–96.
- [11] N. Chand, Properties of lattice matched, strained indium gallium arsenide, INSPEC publication, 1993, pp. 127–129.
- [12] S.R. Andrews, B.A. Miller, J. Appl. Phys. 70 (1991) 993.
- [13] G. Sarusi, B. Brill, SPIE 3436 (1998) 240.